

SHIP PRODUCTION COMMITTEE
FACILITIES AND ENVIRONMENTAL EFFECTS
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EDUCATION AND TRAINING

September 1992
NSRP 0383

THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1992 Ship Production Symposium Proceedings

Paper No. 3A-1: Microbial Biofilm Effects on Drag - Lab and Field

U.S. DEPARTMENT OF THE NAVY
CARDEROCK DIVISION,
NAVAL SURFACE WARFARE CENTER

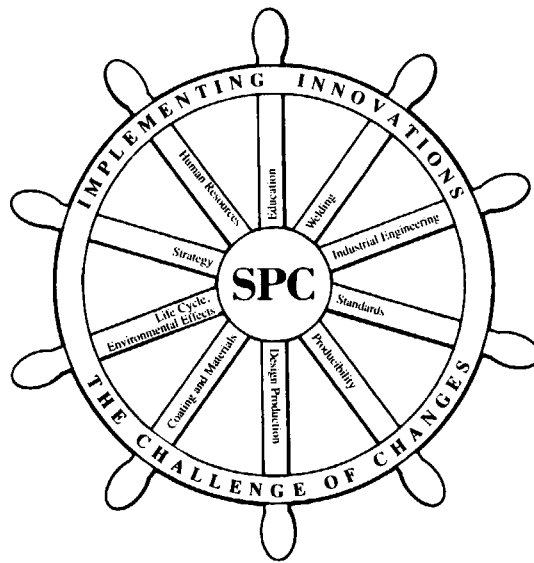
| Report Documentation Page | | | | Form Approved OMB No. 0704-0188 | |
|--|------------------------------------|-------------------------------------|--|--|---------------------------------|
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| 1. REPORT DATE SEP 1992 | | 2. REPORT TYPE N/A | | 3. DATES COVERED - | |
| 4. TITLE AND SUBTITLE The National Shipbuilding Research Program, 1992 Ship Production Symposium Proceedings, Paper No. 3A-1: Microbial Biofilm Effects on Drag - Lab and Field | | | | 5a. CONTRACT NUMBER | |
| | | | | 5b. GRANT NUMBER | |
| | | | | 5c. PROGRAM ELEMENT NUMBER | |
| 6. AUTHOR(S) | | | | 5d. PROJECT NUMBER | |
| | | | | 5e. TASK NUMBER | |
| | | | | 5f. WORK UNIT NUMBER | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Surface Warfare Center CD Code 2230-Design Integration Tools Bldg 192, Room 128 9500 MacArthur Blvd, Bethesda, MD 20817-5000 | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | | | | 10. SPONSOR/MONITOR'S ACRONYM(S) | |
| | | | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) | |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited | | | | | |
| 13. SUPPLEMENTARY NOTES | | | | | |
| 14. ABSTRACT | | | | | |
| 15. SUBJECT TERMS | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT SAR | 18. NUMBER OF PAGES 11 | 19a. NAME OF RESPONSIBLE PERSON |
| a. REPORT unclassified | b. ABSTRACT unclassified | c. THIS PAGE unclassified | | | |

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THE NATIONAL SHIPBUILDING RESEARCH PROGRAM

1992 SHIP PRODUCTION SYMPOSIUM



SEPTEMBER 2 - 4, 1992
New Orleans Hyatt Regency
NEW ORLEANS, LOUISIANA



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601 PAVONIA AVENUE, JERSEY CITY, NJ 07306

Paper presented at the NSRP 1992 ship Production symposium. New Orleans Regency. New Orleans Louisiana September 2-4, 1992

Microbial Biofilm Effects on Drag -Lab and Field

No. 3A-1

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ABSTRACT

Marine fouling on US Navy hulls causes increased propulsive fuel use and refueling frequency, and decreases ship range and speed. Modern antifouling (AF) coatings are effective against hard fouling for relatively long periods, but do accumulate marine microbial biofilms. Therefore, with respect to drag, the focus has recently shifted from hard fouling to microbial biofilms since even thin films can contribute significantly to drag.

Antifouling paints are being evaluated in the laboratory for drag minimization and are ranked based on drag performance with and without biofilm. All paints experienced increased drag after accumulating biofilm. Significant variations in drag and resistance to biofilm accumulation were noted.

Two full scale ship trials were also conducted on U.S. Navy ships to determine the effect of microbial biofilms on ship power and fuel consumption. A significant change in power consumption, ranging from 8 to 18%, was measured by power trials before and after underwater cleaning to remove microbial biofilms from the hull. These data were compared to laboratory experiments.

BACKGROUND

The microbial biofilm, or slime layer, has been shown to increase hydrodynamic drag and therefore fuel consumption (1,21). About \$500M is spent annually propulsive fuel for the United States Navy Fleet, of which about \$75-100M is spent to overcome the hydrodynamic drag due to fouling.

Since the 1940's, the Navy standard antifouling (AF) paint has been Navy Formula 121 (F-121). This coating is 70% by weight cuprous oxide in a vinyl rosin matrix. F-121 has a widely varying service life prior to initial colonization by macrofouling organisms, generally considered to be from 7 to 30 months. This inconsistent performance is due to variability in coating

quality, the many geographical locations where the ships are located, the seasonality of the marine fouling, and the pierside vs. at-sea schedules of the various units. The Navy found the F-121 service life was not compatible with the normal 4-6 year period between ship overhauls. In order to reduce the negative effects of marine macrofouling, the Navy has been conducting underwater hull cleaning since 1978 on all ships. In general a cleaning is ordered when the underwater hull is greater than 10% covered with macrofouling. This operation utilizes Scamp a diver operated underwater cleaning machine which scrubs the hull with 3 rotating brushes. It is estimated that underwater hull cleaning saves about 6% of the Navy's fuel bill, or about \$30M of the annual propulsive fuel loss due to fouling. More recently, however, research and development has responded to the Navy's need for a 5-7 year paint with the development of ablative AF paints. These materials were the first significant performance improvement over F-121 and were first applied to the entire hull of a Navy ship in 1981. The first ablative paints contained tri-organotin compounds as their primary antifouling toxicant. The organotin paints generally provided excellent performance, giving greater than 5 years macrofouling protection in most cases. However, environmental concerns and associated costs have discouraged the use of organotin AF paints by the Navy. Therefore, cuprous oxide containing ablative paints were developed and are now the materials of choice, having been applied to over 130 ships. Based on currently available Fleet data, about 70% of the cuprous oxide ablative AF paints in service are free of serious calcareous fouling.

Although modern AF paints successfully control hard fouling over long periods, it appears that all AF paints permit the attachment and growth of some microbial forms to ship hulls. Therefore, focus has recently shifted from the well-established negative effects of hard fouling to less severe but significant effects of microbial

biofilms on drag. Loeb et al. (1) showed the significant contribution to drag of even very thin microbial films. It is thought that the increased surface profile and viscoelastic nature of microbial biofilms increase drag with respect to a smooth painted surface (3).

The exact relationship between microbial biofilms and drag remains to be defined, yet reducing their deleterious effects has become more important with the introduction of advanced AF paint technology. Some unanswered questions remain such as when and if microbial biofilms should be removed from AF paints, how to predict the drag characteristics of an AF paint, and how much an AF paint can contribute to drag minimization. This paper demonstrates through full-scale power trials and laboratory tests the degree to which marine microbial biofilms contribute to drag, and provides insight into potential solutions to the problems they cause.

MATERIALS AND METHODS - LABORATORY EVALUATION

Twenty-four candidate AF paint systems have been evaluated over a three year period (Table I). Each was applied to 3 duplicate 22.86 cm (9 in.) diameter, 0.3 cm (0.125 in.) thick steel disks. Surface preparation was accomplished by abrasive blasting with 90 mesh aluminum oxide grit with which a 50-75 micron (2-3 mil) profile was obtained. The disks were then either painted in-house or protected from corrosion and sent out to companies to be coated with candidate materials. The AF paints were applied as per manufacturer's specifications. If anticorrosion protection was necessary, formula 150 polyamide epoxy paint, MIL-P-24441, type 1 was used. Paint dry film thickness was measured with an Elcometer 256 gauge.

A friction disk machine (FDM) was used to evaluate disk drag (Fig. 1).

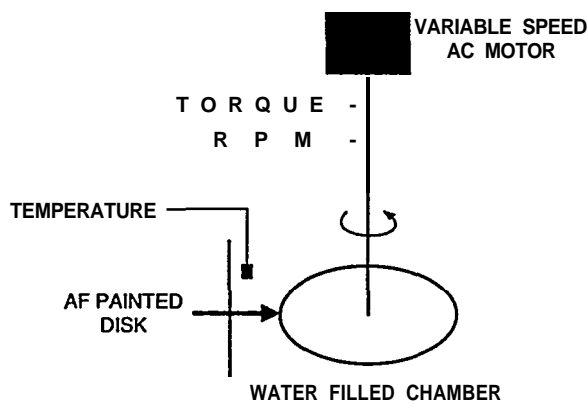


Fig. 1. Friction disk machine (FDM).

The FDM was powered by a variable speed alternating current motor which drove a shaft onto which a disk was mounted. Disks were immersed in a tap water filled chamber during testing. A precision dynamometer installed on the motor shaft measured torque. The disks were evaluated in three conditions: 1) when freshly painted, when the paint was dry, 2) after 4-5 months exposure in brackish water, while slimed, and 3) after removing the remaining slime layer by gentle scraping with a rubber squeegee. Values of temperature, torque, and RPM were recorded for each disk at increments of 200 RPM from 700 to 1500 RPM and then at 200 RPM decrements to 700 RPM to complete the cycle. For each condition tested the disk was taken through this cycle one time except the post-exposure condition. At this stage the spinning action caused some debris and loosely attached biofilm to wash off the post-exposure disks, therefore these disks were taken through the cycle 700-1500-700 RPM two times to ensure equilibrium had been reached. In this case, only data from the second cycle was used in the final data analysis. Disks with significant amounts of macrofouling created too much turbulence in the FDM chamber. Therefore, these disks were considered to have failed and were not evaluated further.

After drag evaluation of the post-exposure condition, a light section microscope (Fig. 2) was used to determine the thickness of the remaining biofilm layer. A microscope coverslip was placed over the wet biofilm before taking a measurement.

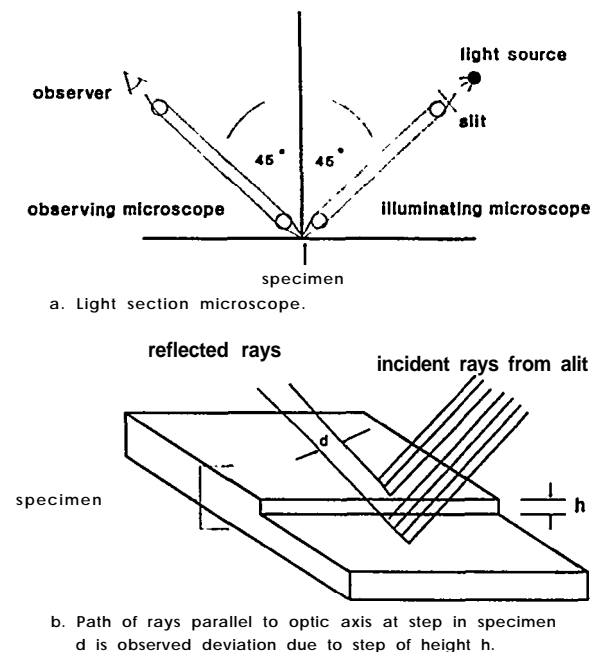


Fig. 2. a. Schematic of light section microscope. b. Detail of light path at specimen.

Prior to and following the spinning of each set of three disks, a standard disk was run to ensure stable operation of the FDM and to correct for bearing drag. The standard disk was made of a titanium 6Al-4Va alloy with a known roughness (Fig. 3).

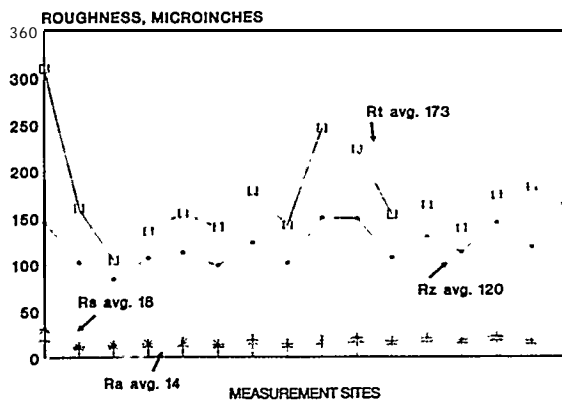


Fig. 3. Surface roughness of titanium disk number T-10.

MATERIALS AND METHODS - SHIPTRIAL

A full scale ship trial was proposed in an attempt to determine the effect of marine microbial biofilms on ship propulsive power and fuel consumption. It was desirable to identify a surface ship that was scheduled to receive an ablative antifouling paint in drydock, and to monitor the newly coated ship until a biofilm layer had been established. USS BREWTON, (FF 1071), a single screw frigate of the KNOX class, was nominated to be the test ship for the trial.

BREWTON, which is homeported in Pearl Harbor, Hawaii, was painted with an ablative AF paint containing both cuprous oxide and tributyltin oxide in October 1987. The ship had a 22 month biofilm on the hull at the time of the power trial. An initial underwater inspection by divers revealed the presence of a visible layer of microbial biofilm over the entire hull. In addition, there was barnacle fouling evident on the keel blocks and side blocks unpainted at the last dry docking, as well as on scattered small areas at the waterline. However, the vast majority of the hull was free of calcareous fouling.

The following sequence was conducted for the full scale power trial to determine the effect of biofilms on ship performance.

1. Initial installation of trial equipment. An Accurex[™] shaft torsion meter was installed to measure shaft torque, from which shaft horsepower would be calculated. An RPM indicator was also installed. Various outputs from ship

instrumentation including rudder angle, wind speed, turbine first stage shell pressure and ship speed from the electromagnetic log were to be recorded. The trial was performed on a "measured mile" course off the west coast of the island of Oahu. Motorola MiniRanger[™] tracking equipment was used on both the tracking range and the ship in order to read ship speed to 0.1 knots and establish location.

2. Diver inspection of the underwater hull. A Navy dive team conducted an inspection of the hull using color video and still photography to record the type and extent of marine fouling. In addition, a hull roughness survey was conducted with a British Maritime Technology (BMT) Hull Roughness Analyzer (HRA) at 50 locations on the hull. Also, the propeller was cleaned and polished to eliminate the effects of propeller fouling on the trial.
3. The initial power trial. The ship transited to the tracking range at high speed to assure that any-loosely attached biofilm and/or debris would wash off the hull. During the trial itself BREWTON was operated at speeds from 12 knots to full power, in 3 knot increments. Three reciprocal runs were made at each speed to negate the effects of wind and current. Williamson turns were made at the end of each run, so that ship rudder angle and heading had stabilized prior to the commencement of each run. Shaft torque, shaft RPM and ship speed were continually recorded for each trial run.
4. The underwater hull cleaning. The SCAMP[™] machine was used to remove the microbial biofilm from the hull. Unlike a routine hull cleaning, the standard cleaning brushes constructed of wire rope were not used. Instead, brushes constructed of polypropylene bristles were used so as to, as far as possible, remove only the microbial biofilm and leave any calcareous forms on the hull. While some small barnacles may have been removed, a post-cleaned inspection showed that the majority remained on the hull.
5. The post-cleaned power trial. The post-cleaned power trial was conducted in an identical manner to the pre-cleaned trial.
6. The post-cleaned inspection. A post-cleaning diver inspection was conducted. Navy divers were utilized to inspect and photograph the hull and to record the hull roughness with the HRA.

DRAG CALCULATIONS - LABORATORY EXPERIMENT

The data indicated that microfouling has a measurable deleterious effect upon hydrodynamic

skin friction, but its quantitative significance was not evident from data on systems as far removed from ships as spinning disks. In order to bridge this gap, the treatment of Granville (4) was applied to the data, which allowed interconversion of drag estimates among spinning disk flow and flat plate flow. The assumption was made that a long flat plate will generate a boundary layer similar to that of an actual ship. On this basis, ship drag over a range of speeds corresponding to the Reynolds number range achieved in the friction disk machine was estimated. The calculation proceeded by characterizing the drag increment of the experimental surface in terms of the quantity Delta B, which expresses the deviation of the frictional drag from that of a smooth rigid surface. Using this theory, the drag effects of microfouling observed with the friction disk machine have been transformed to the expected effects on a flat plate and are expressed in terms of Reynolds number (Re) and moment coefficient (Cm).

The values of kinematic viscosity and density of the tap water used in the chamber were interpolated from data taken from Saunders (5) and Weast (6) respectively. The confinement by the FDM tank walls reduced the measured Cm as compared to that of an unconfined disk. Both the Cm and Re were affected and were therefore multiplied by an appropriate correction factor to account for the confined chamber. A plate length of 100m (361 ft), which is representative of a real ship, was used for the flat plate conversion.

The final evaluation, therefore, compares the three treatments to the reference titanium: pre-exposed (painted), post-exposed (with microbial biofilm), and post-cleaned (with microbial biofilm removed). Relative increases in drag on a given paint system were converted to percent increase in drag and were used to rank coating performance.

RESULTS - LABORATORY EXPERIMENT

These experiments were conducted over three fouling seasons, with approximately 8 coatings tested per year. However, appropriate controls were included each year to correct for differences in biology and instrument variations. A reference disk was used frequently and controlled for changes in bearing drag and instrument variability. Overall variability in reference data was less than 2 percent over the three year period. In addition, a set of F-121 (standard Navy free association cuprous oxide coating) control disks was included each year and results were similar over the range of speeds tested each of the three years (year 1 (11-13%); year 2 (14-21%); year 3 (15-17%)).

Three replicate disks were prepared

and tested for each coating. Within any one year the three replicate disks performed similarly (+/- 3% or less). Therefore, the data for the three was averaged. The graphs presented in Fig. 4 show the relation between rotational velocity, as expressed by (log) rotational Reynolds number (Re), and the drag coefficient (Cm) and are representative of the treatment applied to all disks. Coatings are ranked, however, based on a transformation of this data into percent increase in drag from the pre-exposed painted state to the post-exposed fouled state, therefore taking into account the initial drag contribution of the painted, un-exposed disk. The presence of microbial biofilms was shown to increase drag significantly in all cases. The range of drag increases is fairly broad. The rankings are presented in Table I, and represent data taken at about 25 knots.

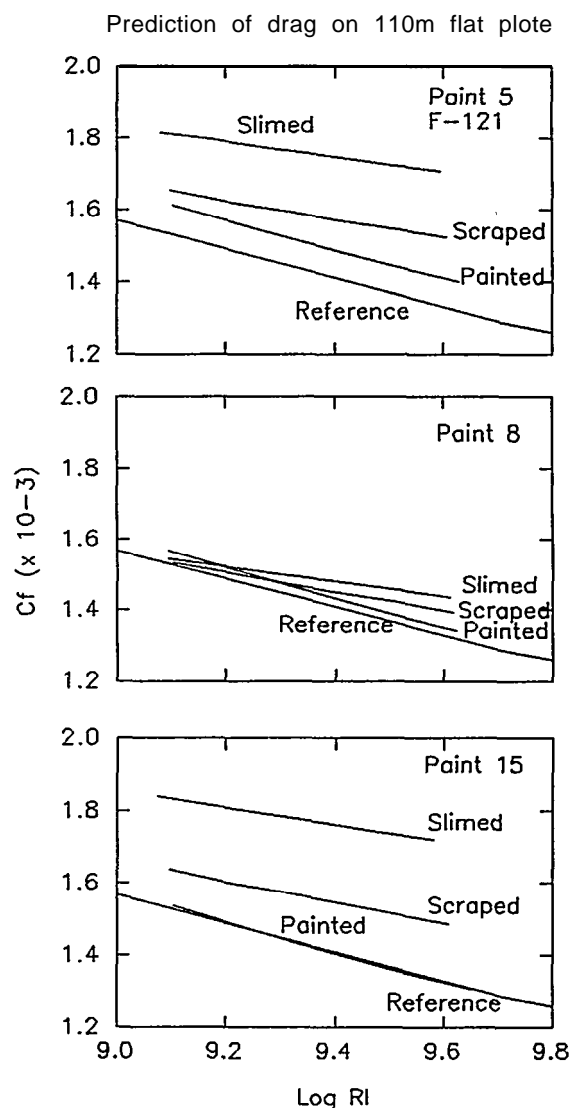


Fig. 4. Prediction of drag on 110 m flat plate.

Table I. AF Paint Systems Tested to Date

| Pnt # | Description | Prf | Rank |
|-------|---------------------------------------|------|----------|
| 1 | Organotin copolymer | G | 9 |
| 2 | Organotin copolymer | G | 6/7 |
| 3 | Organotin | G | 10/11/12 |
| 4 | Cuprous oxide, non-ablative (F-121 A) | G | 6/7 |
| 5 | Cuprous oxide, non-ablative (F-121 B) | G | 10/11/12 |
| 6 | Cuprous oxide, non-ablative (F-121 C) | G | 13 |
| 7 | Cuprous oxide, ablative | G/P | 17 |
| 8 | Cuprous oxide, ablative | VG | 1 |
| 9 | Cuprous oxide, ablative | G | 5 |
| 10 | Cuprous oxide, ablative | G/P | 19 |
| 11 | Cuprous oxide, ablative | VG | 2 |
| 12 | Cuprous oxide, ablative | G/P | 15 |
| 13 | Cuprous oxide, ablative | G | 14 |
| 14 | Cuprous oxide, ablative | G | 10/11/12 |
| 15 | Cuprous oxide, ablative and booster | P | 21 |
| 16 | Cuprous oxide, ablative | G/P | 18 |
| 17 | Cuprous oxide, ablative | P | 20 |
| 18 | Cuprous oxide, ablative and booster | VG/G | 4 |
| 19 | Cuprous oxide, ablative and booster | P | 22 |
| 20 | Cuprous oxide, ablative and booster | VG | 3 |
| 21 | Cuprous oxide + ammonium sulfate | G | 8 |
| 22 | Copper flake | G/P | 16 |
| 23 | Copper flake + booster | F | 23 |
| 24 | Both copper and tin free | F | 24 |

Based on percent drag increment, paints 8, 11, and 20 were the top three performers and paint 15 was the worst performer. The best three coatings showed only a 0-9% increase in drag over the range of speeds tested whereas the worst coating experienced 21-30% increase in drag over the same range of speeds.

Coatings were also placed into performance categories. Coatings which experienced 0-9% increase in drag were considered very good, 10-19% were termed good, and over 20% were poor coatings. In most cases, higher speeds coincided with larger percent increases in drag. Therefore, in some cases coatings fell into more than one performance category over the range of speeds tested (Table I). The majority of coatings tested fit into the good category with 10-19% increase in drag at about 25 knots.

The majority of coatings performed at about the same level as the Navy

standard F-121. However, several coatings out-performed F-121 with respect to drag increment at about 25 knots. Although the majority of coatings experienced a drag increase of about 10-19%, there is room for improvement as evidenced by the top performers- It is expected, therefore, that future coatings development will take into consideration contribution of biofilm to drag.

Biofilm thickness measurements were inconsistent with coatings rankings. However, two of the top three performers did accumulate the thinnest biofilms. Overall, biofilm thickness ranged from about 1.2 mils to 2.7 mils, but there was a relatively large amount of variability within the three replicate disks for any given coating. This parameter, therefore, cannot be used to make significant performance characterizations.

Use of a rubber squeegee to remove remaining biofilm after evaluation in the post-exposure state reduced drag in all cases. In one case a paint returned to the pre-exposed level of drag after cleaning. This data may provide valuable data to ship operators when considering cost effectiveness of underwater hull cleanings and lend insight into their effectiveness.

RESULTS - SHIP TRIAL

There was a significant change in BREWTON's powering characteristics after the underwater hull cleaning to remove the microbial biofilm. Fig. 5 shows a plot of ship speed vs. percent decrease in shaft horsepower required to achieve a given speed as compared to the pre-cleaned condition. There was an 8 to 18 percent decrease in power required to achieve a given speed after the microbial biofilm was removed. The ship's maximum speed increased after cleaning by about 1 knot. The hull roughness, as measured by the HRA, which is a peak to valley measurement over 50mm (2 inches), changed very slightly

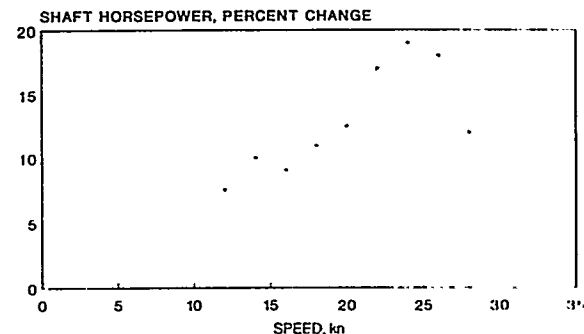


Fig. 5. USS *Brewton* power trial; percent change in shaft horsepower after removal of microbial biofilm.

(Fig. 6), with the mode of the population distribution changing the most.

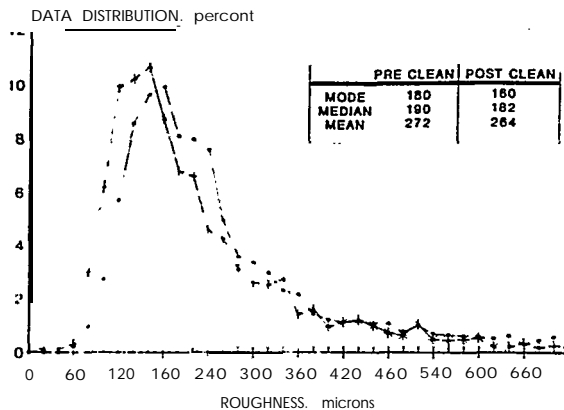


Fig. 6. USS *Brewton* hull roughness comparison pre-clean and post-clean.

When the ship trial data is compared to the laboratory data for the same class of paints, it is interesting to note that the post-cleaned percent decrease in torque to achieve a given speed is comparable (Fig. 7). BREWTON

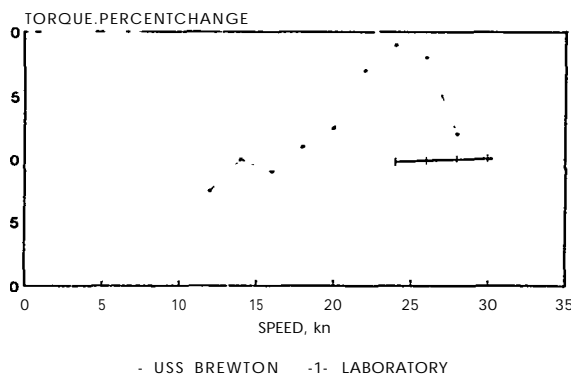


Fig. 7. USS *Brewton* vs. laboratory: power change after cleaning.

required about 18% less shaft horsepower to achieve a speed of 25 knots after an underwater hull cleaning to remove microbial biofilm. In comparison, the laboratory test shows approximately a 10% decrease in torque required to achieve a speed on the FDM equivalent to about 25 knots after the disk was cleaned. More trials are required before a strong correlation between laboratory and field data can be established.

Based on standard fuel consumption curves for the KNOX class, the economics of the cleaning operation were calculated. The \$5600 cleaning cost, for example, would be paid back in fuel savings within a mere 14 to 24 steaming hours over the range of speeds tested (28-12 knots). This represents about

350-600 gallons per hour fuel saved, depending on steaming speed.

CONCLUSIONS

The exact relationship between microbial biofilm properties and drag has not been defined. However, in order to develop a better quantitative understanding of the range of properties and effects of marine biofilms, the hydrodynamic effect of microbial biofilms on the drag of antifouling coatings has been evaluated. The results of the laboratory studies indicate that microfouling does indeed have the potential to significantly increase drag at length scales characteristic of Naval ships. The majority of the coatings tested perform as well as standard Navy coatings, but as evidenced by the top performers there is room for improvement.

In addition, the ship trial demonstrated that removal of a mature marine slime layer on USS BREWTON caused a significant change in the ship powering condition. However, it is not now common practice to conduct underwater hull cleanings on U.S. Navy ships solely for the removal of microbial biofilms. Improvements in cleaning techniques, biofouling detection, and paint technology will play a major role in determining the call for removing microbial biofilms. It seems possible to greatly decrease the drag penalty to ship operators if proper antifouling and hull maintenance measures are adopted.

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